알래스카 툰드라 토양에서 이산화탄소 플럭스의 관측

Co2 Flux from Lichen, Moss, and Tussock Tundra, Council, Alaska

알래스카 주립대학

제 출 문

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본 보고서를 “알래스카 툰드라 토양에서 이산화탄소 플럭스의 관측”과제의 최종 보고서로 제출합니다.

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요 약 문

Ⅰ. 제 목

알래스카 툰드라 토양에서 이산화탄소 플럭스의 관측

Ⅱ. 연구개발의 목적 및 필요성

최근 북극기후환경의 급변으로 인한, 동토의 융해가 뚜렷해지고 있다. 이 동토의 변화는 육상생태계에 식생변화 및 토양환경의 변화를 유발하는 것으로 알려져 있다. 동토융해가 뚜렷한 알래스카 육상생태계에서는 토양기원 이산화탄소의 방출량 정량화를 위하여 신기술인 토양자동개폐시스템(automated CO2 chamber system)을 이용한 연속관측이 요구된다. 또한, 이 시스템은 이전까지 사용된 수동챔버의 단점을 극복할 수 있으며, 시간과 노력대비 효율의 극대화하며, 육상생태계의 탄소순환을 평가하는데 유용하였다. 본 위탁연구는 연속관측 이산화탄소의 관측과 상호/비교/검증을 위하여 일정 실험구(40미터X40미터; 5미터 간격)에서 수동챔버 시스템을 이용하여 이산화탄소 방출량의 시공간분포를 측정하였다.

Ⅲ. 연구개발의 내용 및 범위

자동이산화탄소 개폐시스템은 극지방 환경에 적합한 시스템으로 일차년도에 수정보완한 후, 2차년도에 식생 성장기간동안 토양기원 이산화탄소의 방출량을 수동챔버와 동시에 관측을 행하였다. 지표면의 대표 식생에 대한 시공간적 이산화탄소의 방출량을 정량화 및 상호비교하는데 주력하였다. 단지, 자동챔버개폐시스템에 대해서는 채남이 박사의 주도하에 이루어졌다.

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1. Introduction

CO_2 flux, soil respiration (SR) that is flux of microbially and plant-respired carbon dioxide from the soil surface to the atmosphere, is the second largest carbon emission between the atmosphere and the terrestrial ecosystem on a global scale (Schelsinger and Andrews, 2000; Bond-Lamberty and Thomson, 2010). Recently, Bond-Lamberty and Thomson (2010) estimated that the global CO_2 flux was 98±12 PgC (1 PgC=10^{15} gC) and that it increased by 0.1 PgC/year between 1989 and 2008, implying a global CO_2 flux response to air temperature (Q_{10}) of 1.5. This suggests that their used data consistent with an acceleration of the terrestrial carbon cycle in response to global climate change.

In tundra ecosystem of Alaska, CO_2 flux-measurements by chamber method have been investigated with eddy covariance method by many scientists in response to the Arctic warming for the assessment of soil-originated CO_2 emission to the atmosphere. Tundra ecosystem in the Arctic has focused on the degradation of permafrost and shrinking ponds and lakes response to the Arctic climate change (Romanovsky et al. 2002; Yoshikawa and Hinzman, 2003; Hinzman et al. 2005; Smith et al. 2005), reflecting changes in terrestrial carbon and water cycles (Oechel et al. 2000; Michealson and Ping, 2003; ACIA, 2005; Oberbauer et al. 2007; Walter et al. 2007; Koven et al. 2011).

CO_2 flux in tundra ecosystem depends on the distribution of vegetation and soil organic carbon (SOC) with bioclimate gradient (Michaelson et al. 2008; Ping et al. 2008; Walker et al. 2008). Oechel et al. (1997) and Grogan and Chapin (2000) demonstrated that CO_2 flux in tussock was an order greater than in wet sedge and inter-tussock in the Arctic typical tundra ecosystem. That is, according to the vegetation distribution, CO_2 producing strength will be changed by the different decomposition rate of SOC and by the difference of environmental elements such as soil temperature and soil moisture. Soil temperature and soil moisture are significant roles in determining CO_2 flux in terrestrial ecosystem (Raich and Schlesinger, 1992; Lloyd and Taylor, 1994; Davision and Jassens, 2006; Bond-Lamberty and Thomson, 2010). However, these results can be changed by the methods of CO_2 flux-measurements, depending on chamber size, frequency of hourly, weekly, seasonal, and annual flux-measurements, the flux-measurement system such as automated chamber system and manual system, and so on. Many different methods have been used to measure CO_2 flux with advantages and disadvantages (Davidson et al. 2002; Hutchinson and Livingston, 2002; Savage and Davidson, 2003). Manual chamber measurements are usually made by each person who carries from site to site. These methods cannot be periodically, frequently measured due to the constraints of time, labor, and unexpected weather condition. Nevertheless, these methods have an efficient tool that can be covered wide range to estimate the spatial representativeness of CO_2 flux in targeted vegetation with simplicity of the system. On the other hand, automated chamber systems can simple at a much higher temporal frequency and operate under unexpected weather condition. However, these systems are required greater infrastructure such as constant power supply and storage to run and much expensive than do the manual system. Because of these constraints, the automated chamber systems are more poorly spatial distributed than the manual systems. The manual chamber system can more easily represent the spatial heterogeneity of a site through a year; on the other hand, the automated chamber system affords greater temporal frequency during snow-free period. Here, before the automated chamber system is operated in tundra ecosystem, manual chamber system focuses on the assessment of the spatial representativeness of CO_2 flux from dominant on-ground vegetation (e.g., lichen, moss including sphagnum and feather moss, and tussock tundra) within a 40 m × 40 m plot in Council of Seward Peninsula, Alaska. The objectives of this study are to 1) evaluate the effect of environmental elements (e.g., soil temperature, soil moisture, and thaw depth) on CO_2 flux, and 2) examine the spatial representativeness of CO_2 flux with the manual chamber system.

2. Meterial and Methods

The study site is at Council (64°51’38.3”N; 163°42’39.7”W; 45 masl) on the Seward Peninsula, located about 112 km northeast of Nome, Alaska. This site was selected because there is a relatively smooth transition from forest to tundra underlying discontinuous permafrost regime. Monthly average air temperatures in Nome airport during 1971 to 2010 ranges from -10.5°C in January to 14.6°C in July. Average precipitation is 478 mm, including snowfall (Figure 1; Western Regional Climate Center). During the growing season (June to September) of 2011, average ambient temperature and precipitation are

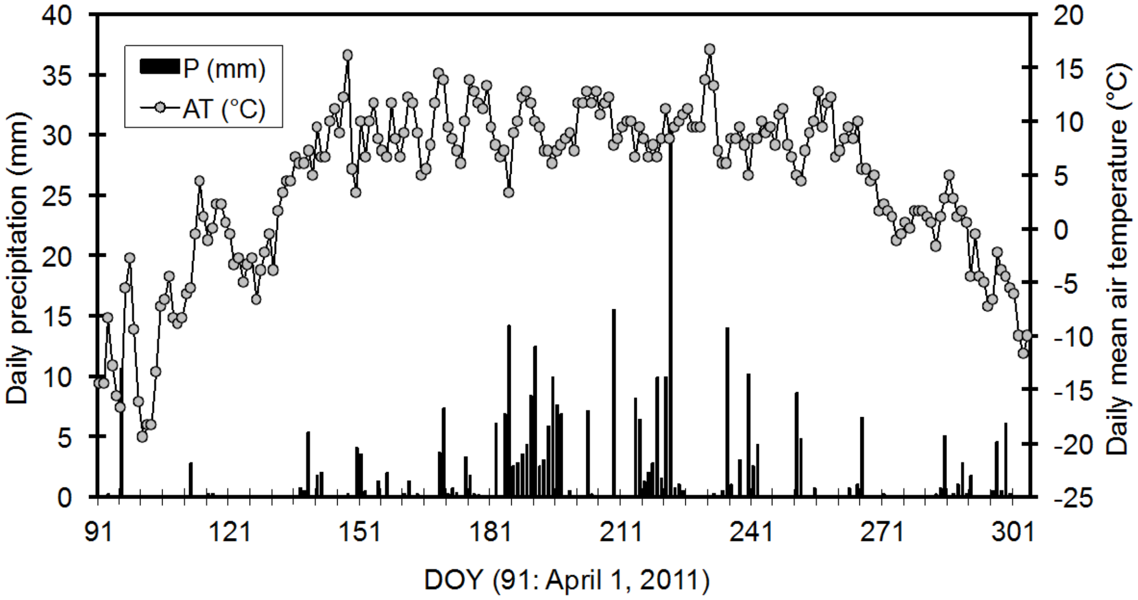

Figure 1. Daily precipitation and average daily ambient temperature in Council, Seward Peninsular, Alaska during April to October of 2011 (Western Regional Climate Center) .

8.9±1.0 °C (CV: 12%) and 285 mm, respectively. Precipitation on July is 120.4 mm, which corresponds to 42% of growing season precipitation and is a 30-year record (Western Regional Climate Center). The DOT (Department Of Transportation) of Alaska has managed the road to access Council from Nome, which opens from late May to early October. Because it was extremely heavy precipitation on July, CO_2 flux-measurement could be not conducted, resulting in the underestimation of CO_2 flux. This study carried out CO_2 flux-measurements in lichen-, moss- and tussock tundra-dominant tundra within a 40 m × 40 m plot (5-m interval; 81 points), Council, Seward Peninsula, Alaska for June, August, and September of 2011. The plot was established for the better understanding in sptaiotemporal variations of CO_2 flux and environmental elements during the growing season. CO_2 flux-measurement was constrained from June to September due to the accessibility of research site. *In-situ* CO_2 flux-measuring system is portable, convenient, and *in-situ* flux calculating. The system is consisted of a transparent-material chamber (24 cm dia. and 8 cm high) with input and output urethane tubing (6 mm OD; 4 mm ID) and a pressure vent, a commercial pump (CM-15-12, Enomoto Micro Pump Co., Ltd., Japan), a NDIR CO_2 analyzer (Licor-820, LICOR Inc., USA), a commercial 12-V battery, 9 chamber bases made of stainless steel (24 cm dia. and 10 cm high) and laptop for the flux calculation. This system is similar to the manual system of Savage and Davidson (2003; see Figure 1). The flux-measuring time in a point is 5 to 10 minutes, depending on the weather and soil surface conditions. The flux was calculated by applying the following equation: $F_{CO2} = (\Delta C/\Delta t) \times (V/A)$, where ΔC is changes in CO_2 concentration during measuring time (Δt), V is chamber volume and A is surface area (0.045 m^2).

Soil temperature of 5 and 10 cm below the surface with a thermometer with two probes (Model 8402-20, Cole-Palmer, USA) and soil moisture were measured in each point with a moisture meter (HH2, Delta-T, UK). Thaw depth with fiberglass tile probe (2m long), and pH meter with waterproof (IQ 160, Ben Meadows, USA) on September were measured. On-ground dominant vegetation (Figure 2) is lichen (*Cladonia mitis, Cladonia crispata,* and *Cladonia stellaris*), moss such as sphagnum moss (*Sphagnum magellanicum, Sphagnum angustifolium,* and *Sphagnum fuscum*) and other mosses (*Polytricum* spp., *Thuidium abietinum*, and *Calliergon* spp.), and cotton grass tussock tundra (*Eriophorum vaginatum*) in 81 points. Dominant lichen, moss and tussock tundra occupy it in 81 points within the plot

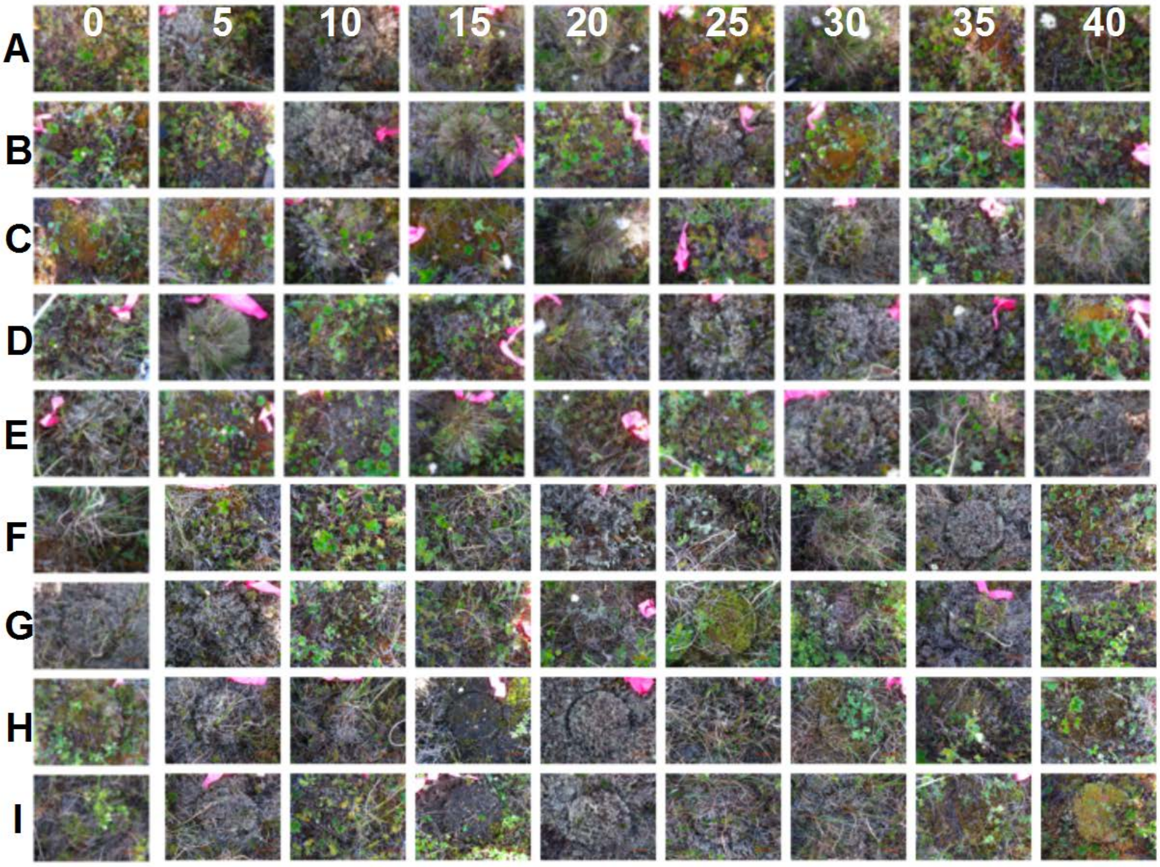

Figure 2. Spatial variations of vegetation in 81 points of a 40 m X 40 m plot, Council, Seward Peninsula, Alaska during the growing season of 2011. .

in 27, 53, and 20%, respectively.

3. Results and Disscusion

3-1 Spatiotemporal variation of CO_2 flux

Average CO_2 fluxes on June, August, and September of 2011 were 8.0±3.6 (Coefficient of Variation: 45%), 3.3±1.3 (CV: 39%), and 2.6±0.8 $mgCO_2/m^2/m$ (CV: 30%), respectively. CO_2 fluxes in lichen and moss ecosystem on August and September are not significantly different based on a one-way ANOVA with a 95% confidence level. CO_2 flux in tussock tundra was approximately 1.5-time higher than those in lichen and moss, which may be due to relatively wider surface area than others. While the surface area in lichen and moss is 0.045 m^2, the area in tussock is 0.085 m^2. It is the reason why higher CO_2 flux in tussock than other vegetation. Spatial variations of CO_2 fluxes on June, August, and September of 2011 were shown in Figure 3, which indicates distinct distribution in CO_2 fluxes within a 40 m × 40 m plot. It may be related to the spatial variations of soil temperature, soil moisture and thaw depth. White and black areas in Figure 3 show higher and lower CO_2 fluxes, indicating the trend that most of white areas are covered by tussock tundra. CO_2 fluxes in Arctic tundra of Alaska ranged 0.38 to 1.6 $mgCO_2/m^2/m$ in lichen, and 0.44 to 4.3 $mgCO_2/m^2/m$ in tussock during the growing season (Poole and Miller, 1982). Table 1 shows average ± standard deviation (CV, %) of CO_2 flux and environmental factors such as soil temperature at 5 and 10 cm below the surface, soil moisture, thaw depth, and pH in lichen, moss, and tussock on June, August, and September of 2011. Due to the waterlogged soil surface on September, pH instead of soil moisture was measured. CO_2 flux decreases the fluctuation and CV values with time, reflecting on an almost constant lower CO_2 production in the soil due to lower soil temperature.

3-2 Spatiotemporal variations of environmental factors

Average soil temperature at 5 and 10 cm below the soil surface were 12.3±3.2 (CV: 53%) and 6.0±3.1 °C (CV: 51%) on June, 8.6±3.1 (CV: 51%) and 5.8±1.4°C (CV: 24%) on August, and 6.6±1.6 (CV: 26%) and 5.3±1.1 °C (CV: 21%) on September, respectively. Spatial variations of soil temperature at 5 and 10 cm below the soil surface were shown in

Figure 4, which spatial trends in soil temperature at 5 and 10 cm are similar to that of CO_2

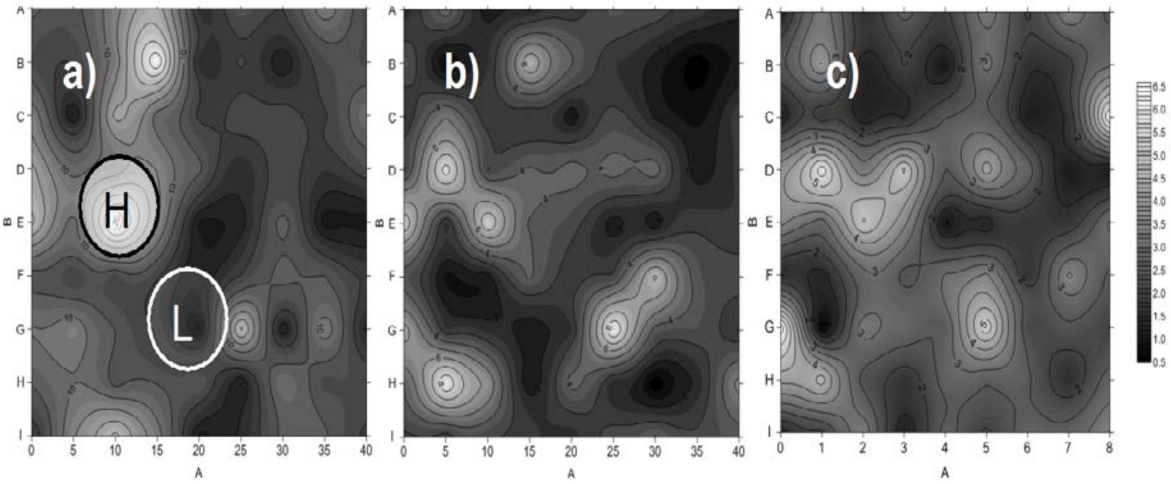

Figure 3. Sptio-temporal variations of CO_2 fluxes within 40 m X 40 m plot, Council, Seward Peninsula, Alaska on a) June, b) August, and c) September of 2011. White and black areas denote high and low CO_2 fluxes.

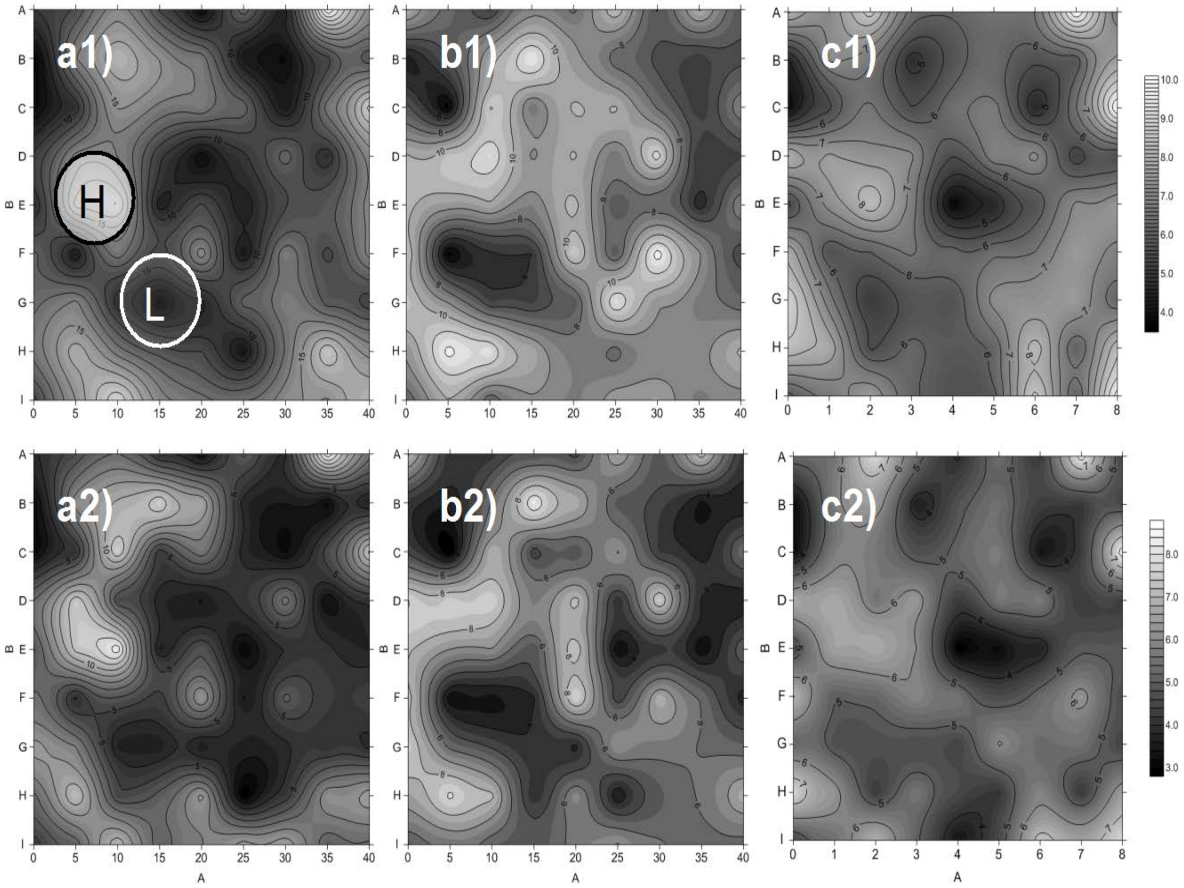

Figure 4. Sptio-temporal variations of soil temperatures at 5 cm (upper) and 10 cm (lower) below the surface within 40 m X 40 m plot, Council, Seward Peninsula, Alaska on a) June, b) August, and c) September of 2011. White and black areas denote high and low temperature.

Table 1. Average ± standard deviation (coefficient of variation, %) of CO_2 flux, soil temperature at 5 and 10 cm below the surface, soil moisture, thaw depth, and pH in lichen, moss, and tussock tundra, Council, Seward Peninsula, Alaska on June, August, and September 2011

Month, 2011	Vegetation	n	CO_2 flux	Soil temperature (°C)		Soil moisture	Thaw depth	pH
			(mgCO_2/m^2/m)	5 cm	10 cm	(m3/m3)	(cm)	
June	Lichen	22	5.7±3.6 (63)	10.1±2.5 (25)	3.3±1.4 (42)	0.270±0.162 (60)	22±3 (12)	n.m.[#]
	Moss	43	7.8±2.2 (29)	13.2±2.9 (22)	6.7±2.8 (42)	0.224±0.122 (54)	21±3 (14)	n.m.
	Tussock	16	12.9±6.2 (48)	12.7±3.3 (26)	7.6±3.7 (48)	0.301±0.116 (39)	22±2 (11)	n.m.
	Average	81*	8.0±3.6 (45)	12.3±3.2 (53)	6.0±3.1 (51)	0.255±0.127 (49)	21±3 (14))	
August	Lichen	24	2.5±1.2 (47)	6.9±1.5 (22)	4.4±1.1 (25)	0.297±0.200 (67)	38±5 (14)	n.m.
	Moss	41	3.3±1.7 (52)	9.0±1.6 (18)	6.2±1.7 (27)	0.264±0.237 (90)	41±8 (19)	n.m.
	Tussock	16	5.1±2.7 (53)	9.4±2.4 (25)	7.0±2.1 (30)	0.256±0.141 (55)	40±5 (12)	n.m.
	Average	81*	3.3±1.3 (39)	8.6±1.9 (22)	5.8±1.4 (24)	0.272±0.180 (66)	40±6 (15)	
September	Lichen	23	2.3±0.9 (40)	6.2±1.0 (16)	4.6±1.0 (21)	- **	57± 8 (13)	3.7±0.4 (7)
	Moss	43	2.5±1.2 (50)	6.9±1.4 (20)	5.6±1.3 (23)	-	58±12 (20)	3.8±0.4 (11)
	Tussock	15	3.5±1.5 (43)	6.5±1.4 (22)	5.2±1.3 (25)	-	55± 5 (8)	3.8±0.3 (8)
	Average	81*	2.6±0.8 (30)	6.0±1.6 (26)	5.3±1.1 (21)	-	57± 9 (16)	3.8±0.4 (11)

* denots total measured points.

** - is not measured due to water-saturated soil.

[#] n.m. indicates not measured due to dry condition.

flux. It suggests that soil temperature is one of significant factors in modulating CO_2 flux. Average soil moisture and pH were 0.255±0.127 (CV: 49%) and 0.272±0.180 (CV: 66%) m^3/m^3 on June and August, 3.8±0.4 (CV: 11%) on September, respectively (Figure 5: upper plate). Spatial variation of soil moisture shows inverse distributions on CO_2 flux and soil temperature. Average thaw depth was 21±3 (CV: 14%), 40±6 (CV: 15%), and 57±9 (CV: 16%) on June, August, and September (Figure 5: lower plate), respectively. The average thawing rate in soil from June to September is 0.45 cm/day, which is similar to those from June to August, and from August to September. Spatial variation of thaw depth indicates similar distribution of soil moisture.

3-3 Environmental factors regulating CO_2 flux

CO_2 flux is regulated by the soil temperature as shown in Figure 6. Relationships between CO_2 flux and soil temperature at 5 and 10 cm below the surface in lichen and moss have exponential curves on June, August, and September. On the other hand, the relationship in tussock tundra has linear. Q_{10} is the temperature coefficient of the reaction and is defined as the ratio of reaction rate at an interval of 10 °C. Van’t Hoff formulated the empirical rule is on the order of 2 to 3. Table 2 shows Q_{10} values and correlation coefficients (R^2) from the relationship between CO_2 flux and soil temperature at 5 and 10 cm below the surface in lichen, moss, and tussock tundra based on a one-way ANOVA with a 95% confidence level. Conveniently, Q_{10} values on tussock are estimated by the exponential curve as shown in Table 2. Q_{10} values increase with time, suggesting CO_2 production by soil microbes and root has greater sensitive to narrower range of soil temperature. Soil moisture has much weaker relationship to CO_2 flux in lichen, moss, and tussock on each month (< R^2 of 0.06). While thaw depths have negative linear ration to CO_2 fluxes in lichen on June, in moss on August and September, and in tussock on June (R^2: 0.09 to 0.25), thaw depths in lichen on August, in moss on June, and in tussock on September have positive lines with CO_2 flux (R^2: 0.13 to 0.26). Moreover, relationship between soil temperature at 5 cm and soil moisture is less than 0.15 (R^2), indicating that soil moisture is not affected to soil temperature.

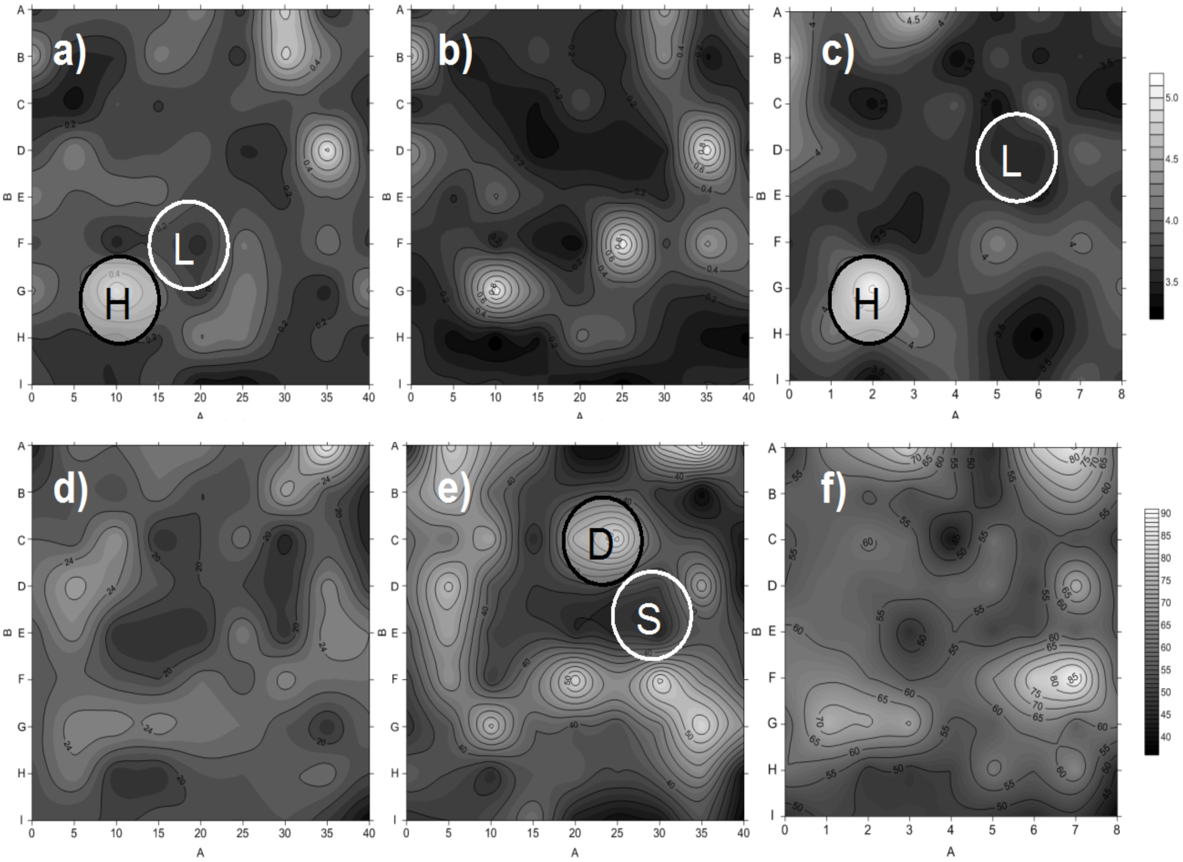

Figure 5. Sptio-temporal variations of soil moisture (a and b) and pH (c) (upper panel), and thaw depth (lower) within 40 m X 40 m plot, Council, Seward Peninsula, Alaska on June (a and d), August (b and e), and September of 2011. White and black areas denote high and low soil moisture and pH, and deep and shallow thaw depth.

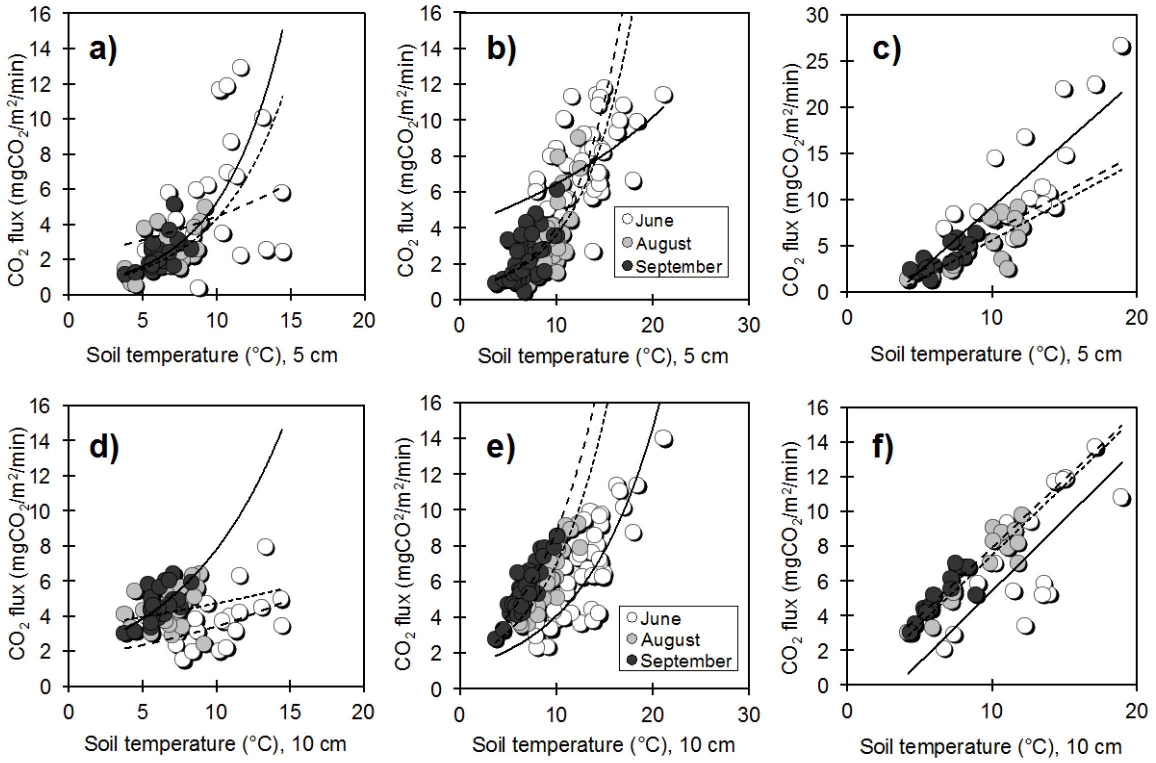

Figure 6. Relationship between CO$_2$ flux and soil temperature at 5 cm (upper) and 10 cm (lower) below the surface in lichen (a and d) , moss (b and e), tussock tundra (and c and f), Council, Alaska on June (open circles; solid line), August (grey circles; dotted line), and September (black circles; dashed line) of 2011.

Table 2. Q_{10} values and correlation coefficient between CO_2 flux and soil temperature at 5 and 10 cm below the soil surface in lichen, moss, and tussock during the growing season based on a one-way ANOVA with a 95% confidence level

Vegetation	Month	5 cm			10 cm		
		Q_{10}	R^2	*p*	Q_{10}	R^2	*p*
Lichen	June	2.05	0.10	<0.001	2.12	0.22	0.018
	August	8.58	0.36	<0.001	1.43	0.04	<0.001
	September	10.59	0.43	<0.001	4.10	0.43	<0.001
	Average	4.97	0.34	<0.001	1.04	0.01	0.032
Moss	June	1.58	0.26	<0.001	3.58	0.67	0.073
	August	6.59	0.40	<0.001	4.76	0.78	<0.001
	September	7.54	0.28	<0.001	4.53	0.78	<0.001
	Average	5.05	0.62	<0.002	1.85	0.37	<0.001
Tussock	June	2.68	0.54	0.890	3.59	0.57	0.005
	August	8.66	0.68	<0.001	4.03	0.86	0.041
	September	10.74	0.58	<0.001	4.93	0.75	0.008
	Average	6.15	0.73	0.018	2.42	0.53	0.467

3-4 Contribution of Tussock tundra

As previously described, there is difference in surface area that is the greater area in tussock tundra than in lichen and moss. The surface area in tussock of cone type is approximately 2-time higher than other on-ground vegetation. In Arctic tundra of Alaska, Oechel et al. (1997) estimated 9.9 and 1.0 $mgCO_2/m^2/m$ in tussock and wet sedge during the growing season, demonstrating CO_2 flux in tussock is a significant atmospheric CO_2 source. Also, average daily CO_2 flux from wet sedge followed soil surface temperature closely, and increased exponentially as soil surface temperature increased, while the flux from tussock tundra ecosystem followed soil surface temperature nearly logarithmically (Oechel et al. 1997). The surface area of chamber was 0.56 m^2, which is an order higher than that used in this study. If two tussocks are covered by the chamber, the relationship will be changed to logarithmic from exponential, indicating at least 4-time greater than lichen and moss for the estimation of CO_2 flux. Therefore, CO_2 flux in tussock, which circumpolar area of tussock tundra equal to 9×10^{11} m^2 (Miller et al. 1983) and the area of tussock and moss equal to 6.5×10^{12} m^2 (Whalen and Reeburgh, 1988), provides a quantitative understanding of atmospheric CO_2 source from on-ground tundra of Arctic terrestrial ecosystem.

3-5 Representativeness of CO_2 flux in tundra

Spatial variations of CO_2 fluxes relevant to chamber measurements are often on the scale of centimeters, reflecting the sizes of rocks, disturbances by soil fauna, pockets of fine root proliferation, and remnants of decomposing organic mater (Davidson et al. 2002). In this study, the CV ranged from 29 to 63% with static chamber and decreased with increasing chamber number used. The area covered by a chamber influences the number of chambers required to estimate representativeness on-ground CO_2 fluxes from lichen, moss, and tussock tundra. To estimate the number of sampling points required for each approach at various degrees of precision at a specific level, the following equation: $n = [ts/D]^2$, where n is the sampling point requirement, t is the t-statistic for a given confidence level and degrees of freedom, s is the standard deviation of the full samples of measurement, and D is the desired interval about the full sample average in which a smaller sample average is expected to fall. The results in Table 3 demonstrate that 16, 13, and 8 sampling points on June, August, and September are required for the static chamber system at 81 points to gain an

Table 3. Number of required sampling points for static chamber on different vegetation to achieve different degrees of precision (within±10% to 20% of full sample average) with 80 and 95% confidence level

Month, 2011	Vegetation	No. of actually measured points	CO_2 flux ($mgCO_2/m^2/m$)		80%		95%	
			Average	S.D.	Within ±10%	Within ±20%	Within ±10%	Within ±20%
June	Lichen	22	5.7	3.6	70	17	173	43
	Moss	43	7.8	2.2	13	3	31	8
	Tussock	16	12.9	6.2	42	10	105	26
	Average	81	8.0	3.6	28	7	64	16
August	Lichen	24	2.5	1.2	40	10	99	25
	Moss	41	3.3	1.7	44	11	102	25
	Tussock	16	5.1	2.7	51	13	129	32
	Average	81	3.3	1.3	21	5	50	13
September	Lichen	23	2.3	0.9	27	7	66	16
	Moss	43	2.5	1.2	38	9	89	22
	Tussock	15	3.5	1.5	33	8	85	21
	Average	81	2.6	0.8	13	3	31	8

experimental average that falls within ±20% of full sample average with 95% confidence level; and that 64, 50, and 31 sampling points are required to achieve ±10% with 95% confidence level. This type of intensive study can help guide researchers to determine how many flux measurements are routinely needed per site and date, depending on what spatial or temporal differences that the study is attempting to identify and at what level of statistical confidence (Davidson et al. 2002). Large numbers of flux-measurements are ideal, but logistical constraints of labor and time often limit the number of measurements that are feasible. In order to overcome the logistical constraints, we need to find the characterization of homogeneous or heterogeneous site with static chamber within a 40 m × 40 m plot (2.5- or 5-m interval), and subsequently to perform representative flux-measurements with automated chamber that consists of 16 chambers (surface area: 0.2 m^2) in average points for the spatiotemporal representativeness of the site.

4. Conclusion

Due to the spatial heteorogeneous CO_2 flux, the manual chamber system provides a better understanding of spatial representativeness of CO_2 fluxes from lichen, moss and tussock tundra within a 40 m × 40 m plot (5-m interval: 81 points), Council, Seward Peninsula, Alaska. CO_2 flux in tussock tundra is much higher than in lichen and moss, suggesting that the surface area in tussock is 2-time greater that others. That demonstrates CO_2 flux in tussock has a linear relation to soil temperature at 5 and 10 cm below the surface, while the fluxes from lichen and moss have exponential curve with soil temperature. Considering that the distribution of tussock and other vegetation, these fluxes are significant sources on the atmospheric CO_2 and is imporatant on terrestrial ecosystem carbob dynamics.

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(뒷면)	(측면)	(앞면)
주 의 (편집순서8) (16 포인트 고딕체) ↑ 7cm ↓	알래스카 툰드라토양에서 이산화탄소 플럭스의 관측 알래스카주립대학 ↑ 5cm ↓	↑ 7cm ↓ **알래스카 툰드라 토양에서 이산화탄소 플럭스의 관측** (20 포인트 중고딕체) CO_2 flux from lichen, moss, and tussock tundra, Council, Alaska (16 포인트 명조체) **알래스카주립대학** (20 포인트 중고딕체) ↓ 7cm ↑

주 의

1. 이 보고서는 극지연구소 위탁연구기관에서 수행한 연구결과보고서 입니다.

2. 이 보고서 내용을 발표할 때에는 반드시 극지연구소에서 수행한 위탁연구의 연구결과임을 밝혀야 합니다.

3. 국가과학기술 기밀유지에 필요한 내용은 대외적으로 발표 또는 공개하여서는 안됩니다.